Parameters Affecting the Performance of a Residential-Scale Stationary Fuel Cell System

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May 23-25, 2005

3rd International Conference on Fuel Cell Science, Engineering and Technology, Ypsilanti, MI

Residential Fuel Cell Test Facility Project

Goal: Develop a rating methodology that allows consumers to judge the economic impact of a residential fuel cell system

- Test performance of residential-scale stationary fuel cell systems
- Create empirical performance model
- Draft a rating methodology
- Disseminate results
  - IEA Annex 42 - Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems
  - Fuel cell manufacturers
  - Research community

Performance Testing of Residential Fuel Cells

Plug Power Gensys 5c

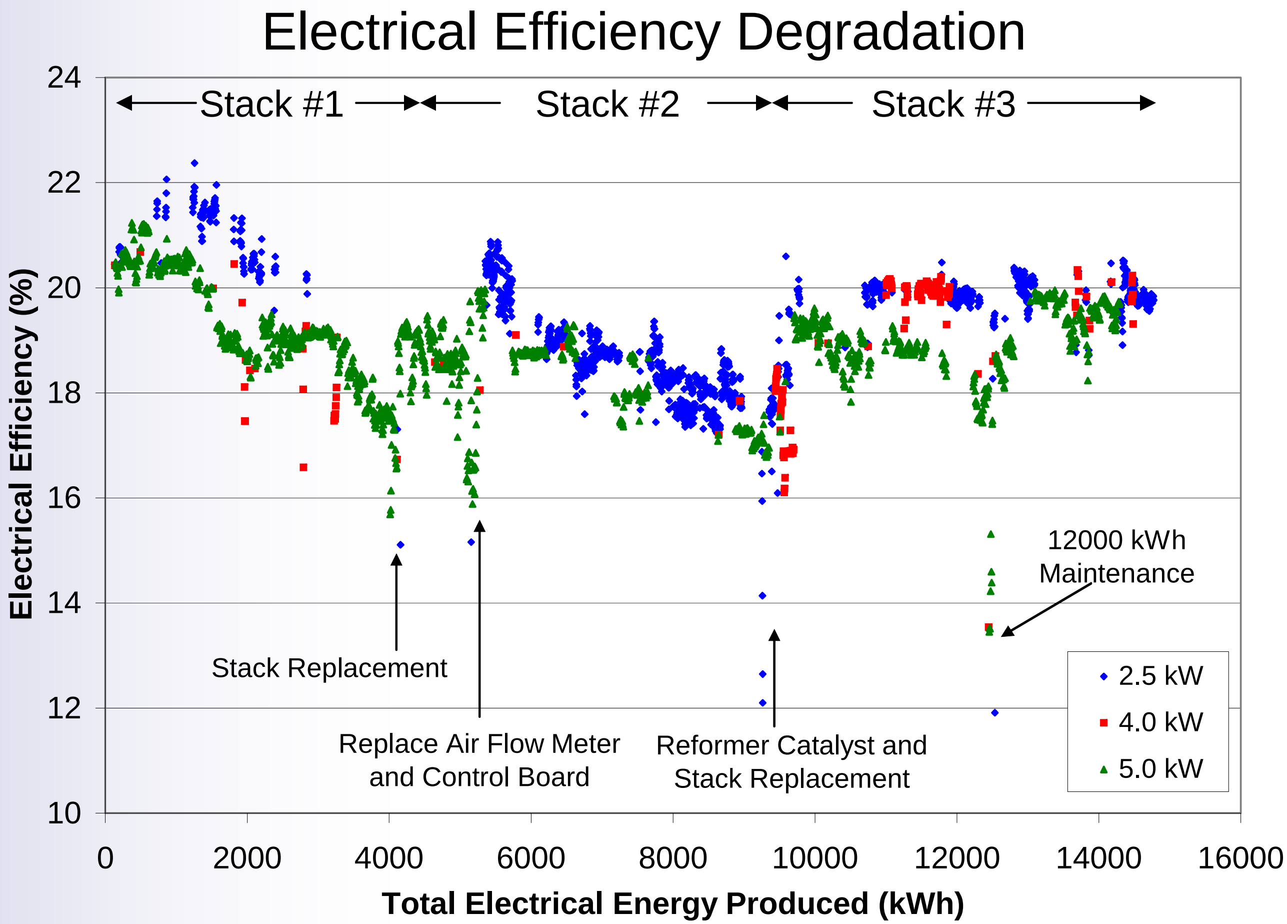
- **Completed testing of Plug Power Gensys 5c**
- Provides base load electrical power and thermal energy
- 5 kW electrical power
- >9 kW thermal power
- Fueled by natural gas
- Grid-interconnected or grid-independent

Performance Testing of Residential Fuel Cells

Plug Power Gensys 5c Performance Results

- Parameters affecting electrical efficiency
  - Electrical load
  - Degradation over time
- Parameters affecting thermal efficiency
  - Electrical load
  - Ambient temperature
  - Fluid flow rate
  - Fluid inlet temperature
- Transient performance insignificant in context of rating methodology

Performance Testing of Residential Fuel Cells



- Sharp decline in efficiency with first two fuel cell stacks made testing difficult
- Replacement of catalyst provided significantly more stable performance

Performance Testing of Residential Fuel Cells

"Bracketing" Test Method

- Original test plan included weekly "baseline" test to quantify degradation, but could not distinguish changes in performance from parameters from changes in performance from degradation

- Developed "bracketing" test method
  - Measure performance at one set of conditions
  - Change a level on a single parameter, and measure steady-state performance
  - Return changed parameter to original level and measure steady-state performance
  - Valid test bracket will have electrical and thermal efficiencies that differ no more than the respective measurement uncertainty

- "Bracket" method ensures that any statistically significant change in performance can be linked to the parameter change

Performance Testing of Residential Fuel Cells

Steady-State Electrical Load Fraction Test

Grid-Interconnected

Electrical Load Fraction (%)	Electrical Efficiency (%)	Measurement Uncertainty (%)	Relative Perform. Index
100	19.4	0.16	
50	20.0	0.17	**1.04**
80	19.8	0.20	**1.03**
100	19.1	0.18	

Grid-Independent

Electrical Load Fraction (%)	Electrical Efficiency (%)	Measurement Uncertainty (%)	Relative Perform. Index
100	18.7	0.17	
50	18.8	0.15	1.01
80	19.5	0.15	**1.04**
100	18.7	0.14	

Performance Testing of Residential Fuel Cells

Thermal Load Parametric Testing

- Steady-state testing to determine the effects of the heat transfer fluid flow rate and inlet temperature
- Set of 10 tests performed at:
  - 2 electrical power levels (50% and 100%)
  - 4 combinations of ambient temperature and relative humidity
  - 80 tests!
- Relative change in performance within bracket calculated

Bracket #	Flow (LPM)	Temp (°C)
	35	55
I	5	55
	35	55
II	35	18
	35	55
	5	18
III	35	18
	5	18
IV	5	55
	5	18

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Performance Testing of Residential Fuel Cells

Electrical Efficiency at Various Thermal Loads

Bracket ID	Fluid Flow Rate (LPM)	Fluid Inlet Temp (°C)	Ambient Temperature = 35 °C								Ambient Temperature = 11.5°C							
			RH = 40%				RH = 75%				RH = 55%				RH = 25%			
			LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%	
			η_e	Index	η_e	Index	η_e	Index	η_e	Index	η_e	Index	η_e	Index	η_e	Index	η_e	Index
I	35	55	18.0		20.1		16.8		20.2		18.6		19.5		18.5		19.5	
	5	55	18.1	1.00	20.2	1.00	16.4	0.99	20.1	0.99	18.4	0.99	b		19.0	1.03	b	
	35	55	18.3		20.2		16.4 / 19.5		20.4		18.4		19.4		18.4		18.3	
II	35	18	18.4	0.99	20.3	1.00	19.2	a	20.4	1.00	18.1	0.99	19.2	0.99	18.7	1.01	18.3	1.01
	35	55	18.8		20.2		17.4		20.2		18.2		19.5		18.7		18.1	
III	5	18	18.7		20.2		18.5		20.7		17.5		19.4		18.4		19.5	
	35	18	18.9	1.00	20.1	1.00	18.6	1.00	20.6	1.00	17.2	0.99	19.6	1.01	18.7	1.01	19.7	a
	5	18	19.1		20.1		18.8		20.7		17.4		19.5		18.5		19.9	
IV	5	55	19.0	1.00	19.9	0.99	17.8	a	20.2	a	17.5	1.02	b		18.3	0.99	b	
	5	18	18.8		20.2		17.0		20.1		17.2		19.8		18.5		19.6	

- Parametric testing showed that none of the parameter changes affected the electrical efficiency
- We can conclude that the electrical efficiency is independent of the thermal load

Performance Testing of Residential Fuel Cells

Thermal Energy Extraction Investigation

Load Fraction (%)	Fluid Flow Rate (LPM)	Fluid Inlet Temperature (°C)	Electrical Efficiency (%)	Thermal Efficency (%)	Overall Efficiency (%)
50	35	55	**19.8**	**19.4**	**39.2**
50	0	0	**19.7**	**0.0**	**19.7**
50	35	55	**19.8**	**19.3**	**39.2**
80	35	55	**20.0**	**28.1**	**48.1**
80	0	0	**20.0**	**0.0**	**20.0**
80	35	55	**20.0**	**28.2**	**48.2**
100	35	55	**18.9**	**32.1**	**51.0**
100	0	0	**19.0**	**0.0**	**19.0**
100	35	55	**19.0**	**32.1**	**51.0**

Extraction of thermal energy has no affect on the electrical efficiency of the system

Performance Testing of Residential Fuel Cells

Thermal Efficiency at Various Thermal Loads

Bracket ID	Fluid Flow Rate (LPM)	Fluid Inlet Temp (°C)	Ambient Temperature = 35 °C								Ambient Temperature = 11.5°C							
			RH = 40%				RH = 75%				RH = 55%				RH = 25%			
			LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%	
			η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index
I	35	55	39.2	**0.28**	37.2	**0.58**	36.8	**0.28**	35.9	**0.59**	36.6	**0.31**	28.9		36.8	**0.31**	29.6	
	5	55	10.9		21.5		10.0		21.2		11.5		b		11.6		b	
	35	55	39.6		37.3		36.0 39.9		36.4		36.4		28.8		37.1		23.5	
II	35	18	42.9	**1.08**	42.6	**1.15**	45.9	a	43.7	**1.21**	42.3	**1.16**	34.5	**1.22**	41.2	**1.11**	34.6	**1.48**
	35	55	39.7		36.8		37.8		36.0		36.7		27.8		37.1		23.4	
III	5	18	44.5	0.98	44.0	0.96	45.9	1.04	46.1	0.97	43.7	1.03	35.5	0.95	41.4	0.98	36.8	a
	35	18	43.6		42.5		47.9		44.3		44.2		34.0		40.6		35.7	
	5	18	44.8		44.5		46.5		45.6		42.4		35.7		41.6		37.6	
IV	5	55	11.5	**0.26**	21.4	**0.48**	10.8	a	22.1	a	10.9	**0.25**	b		11.2	**0.27**	b	
	5	18	44.8		45.3		45.6		45.5		44.2		37.3		41.8		38.0	

- Thermal efficiency varies between 10% and 48%
- High temperature / low flow rate conditions result in outlet temperature at maximum possible value, which limits the

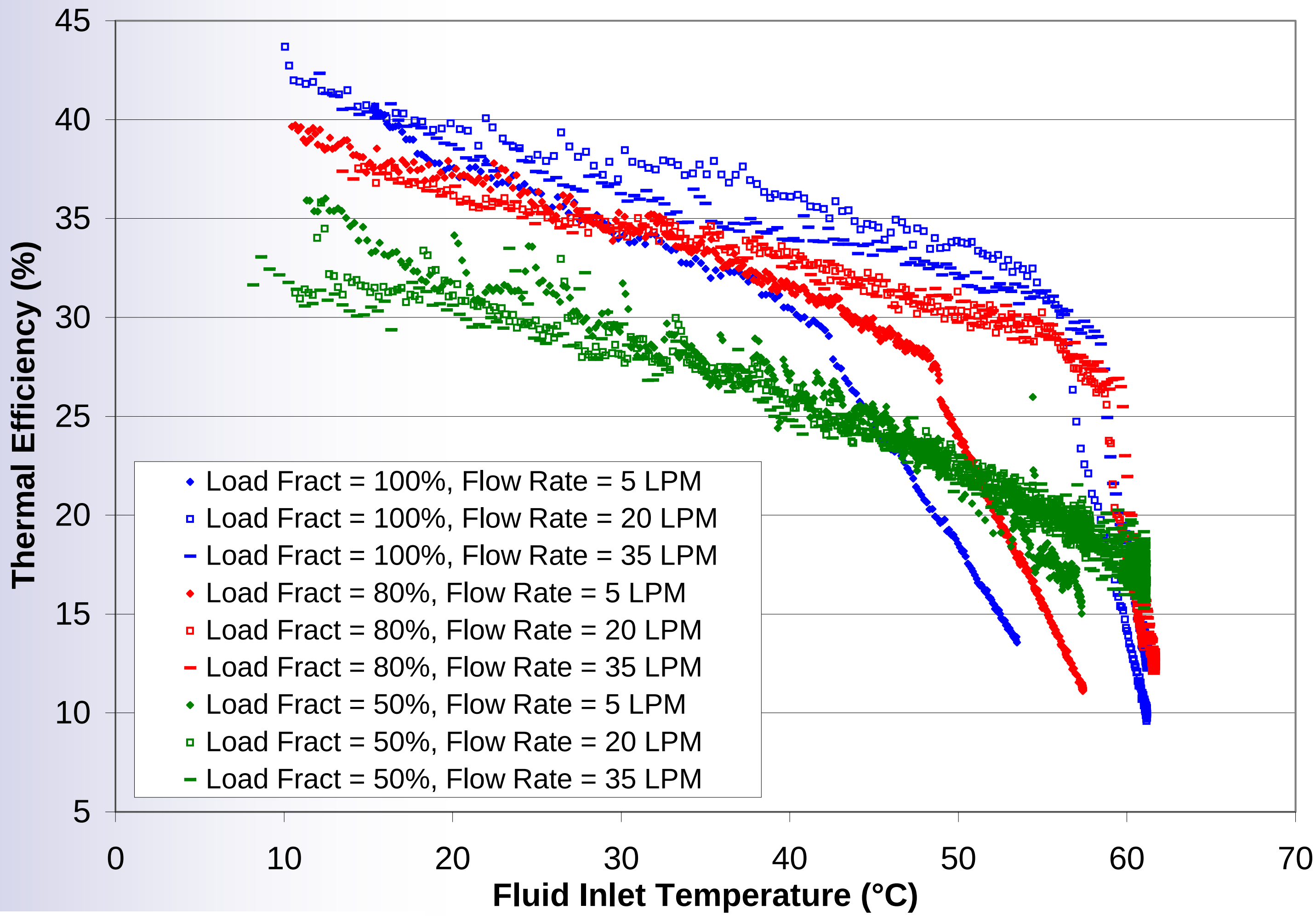
Performance Testing of Residential Fuel Cells

Fluid Temperature Rise Test

- 900+ liters of heat transfer fluid (35% propylene glycol – 65% water) cooled below 18°C
- Fuel cell used to slowly heat fluid, which provides quasi-steady measurement of thermal efficiency versus inlet temperature
- One full test lasts > 18 hours and 10°C step change in fluid reaches steady state in about 5 minutes
  - i.e. test is a valid measure of steady-state thermal performance because the time constant for thermal output is much smaller than the test duration
- Test performed at three flow rates and three electrical power outputs

Performance Testing of Residential Fuel Cells

Fluid Temperature Rise Test



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Performance Testing of Residential Fuel Cells

Ambient Condition Tests

Load Fraction (%)	Ambient Temperature (°C)	Ambient RH (%)	Electrical Performance: Efficiency (%)	Electrical Performance: Relative Index	Thermal Performance: Efficiency (%)	Thermal Performance: Relative Index
50	35	**40**	**18.1**		**37.0**	
50	35	**75**	**18.3**	1.01	**37.4**	1.02
50	35	**40**	**18.0**		**36.5**	
50	**35**	40	**17.8**		**37.1**	
50	**5**	40	**18.2**	1.01	**26.0**	**0.70**
50	**35**	40	**18.2**		**37.0**	
100	35	**40**	**18.3**		**36.6**	
100	35	**75**	**18.8**	1.01	**36.6**	0.99
100	35	**40**	**18.9**		**37.0**	
100	**35**	40	**18.6**		**36.7**	
100	**5**	40	**18.8**	1.02	**29.9**	**0.82**
100	**35**	40	**18.4**		**36.2**	

- Ambient temperature strongly affects the thermal efficiency of the system, but not its electrical efficiency
- Relative humidity has no effect on either the electrical or thermal efficiency

Performance Testing of Residential Fuel Cells

Real World Thermal Load Simulations

- Fuel cell used to preheat thermal storage tank (300 liters)
- Thermal storage tank supplies auxiliary electric water heater (190 liters)
- Water drawn from aux. water heater onto scale in weigh tank
- Fuel cell allowed to continue operating after maximum fluid temperature was reached
- Real world simulation data taken at 5 second intervals

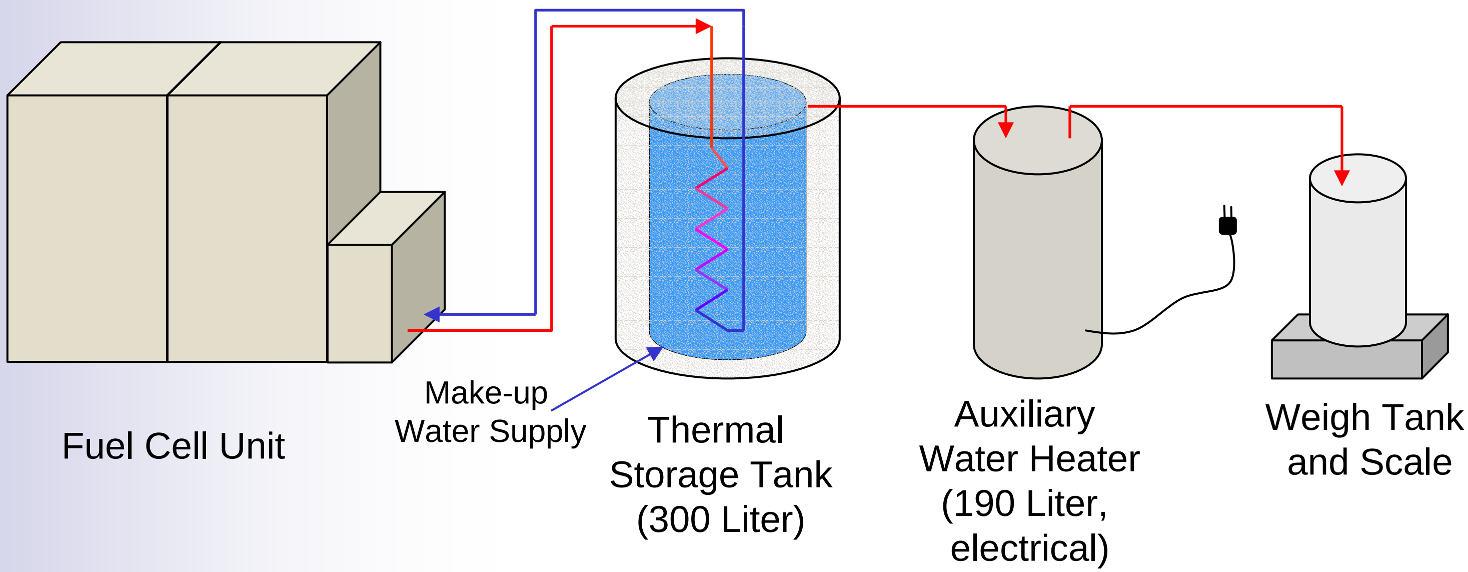
Performance Testing of Residential Fuel Cells

Real World Thermal Load Simulations

- Domestic hot water load simulated by US DOE water heater test procedure
- Test performed at two electrical power levels and two flow rates
  - Electrical load fraction: 50% and 100%
  - Fluid flow rate: 5 LPM and 28 LPM

- Space heating load derived from DOE2 simulation of "typical" house, which was compiled from US housing and energy use statistics
  - House modeled in Syracuse and Atlanta
  - Peak heating day chosen for space heating load
- Weigh tank system not suitable for larger thermal loads
  - Only one space heating test is valid
  - "Invalid" space heating tests still helpful to model validation efforts

Simulated Domestic Hot Water System



- Domestic hot water simulation: 6 hourly draws of 38 Liters followed by 18 hours without a draw
- Space heating load: draw hourly to satisfy thermal load profile

Performance Testing of Residential Fuel Cells

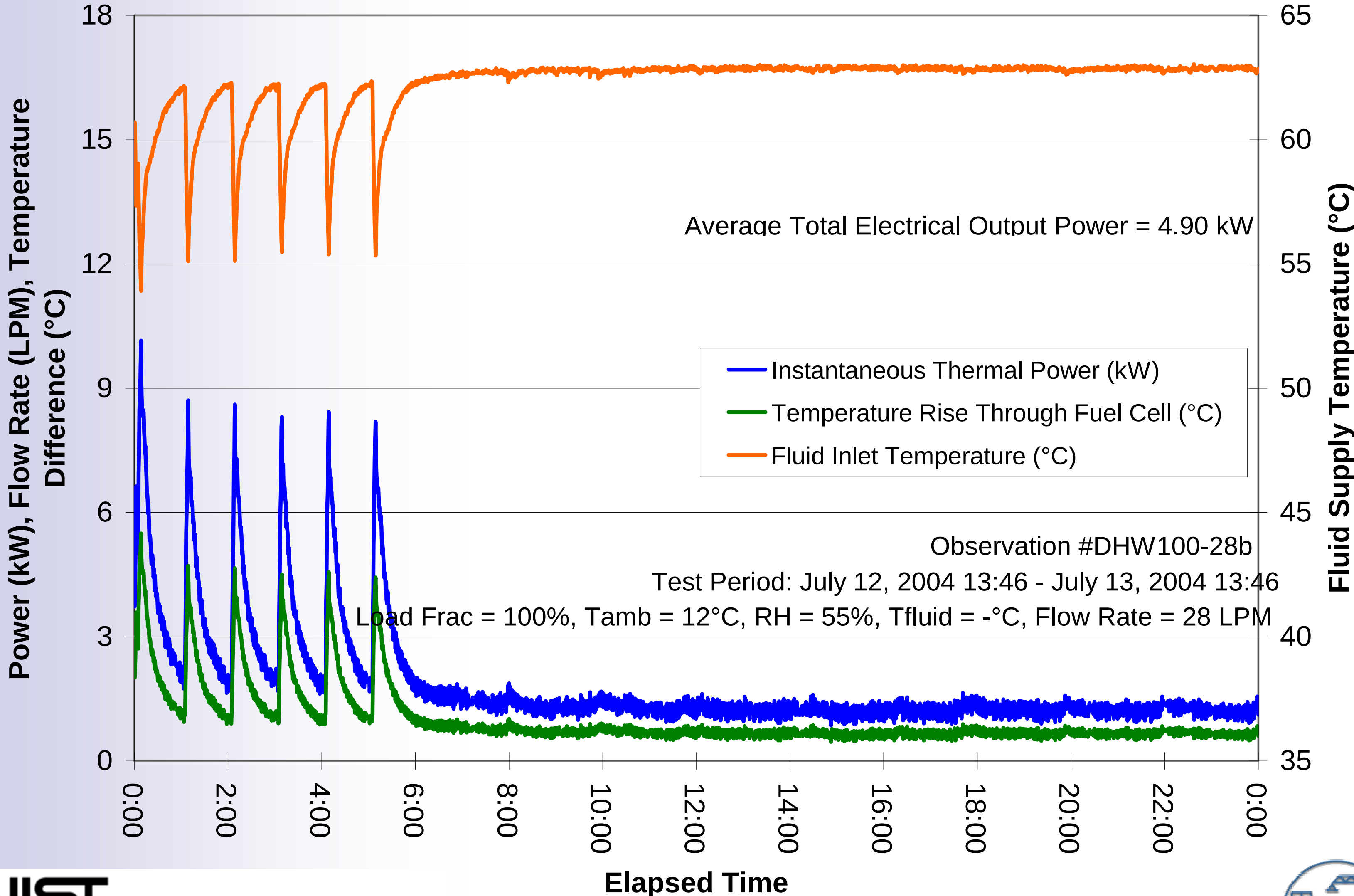
Real-World Thermal Load Simulations

	Domestic Hot Water Load		Space Heating Load
	Load Fraction		
Efficiency	**50 %**	**100 %**	**100 %**
Electrical	18.1	17.2	19.5
Thermal	13.7	6.6	23.6
Overall	31.8	23.8	43.2

- Overall efficiency strongly depends on quantity of thermal load applied to system
- Even space heating load falls short of thermal output capacity of the system, which can achieve overall efficiencies of 68 %

Performance Testing of Residential Fuel Cells

DHW Cogen Temperatures – 100% Load Fraction



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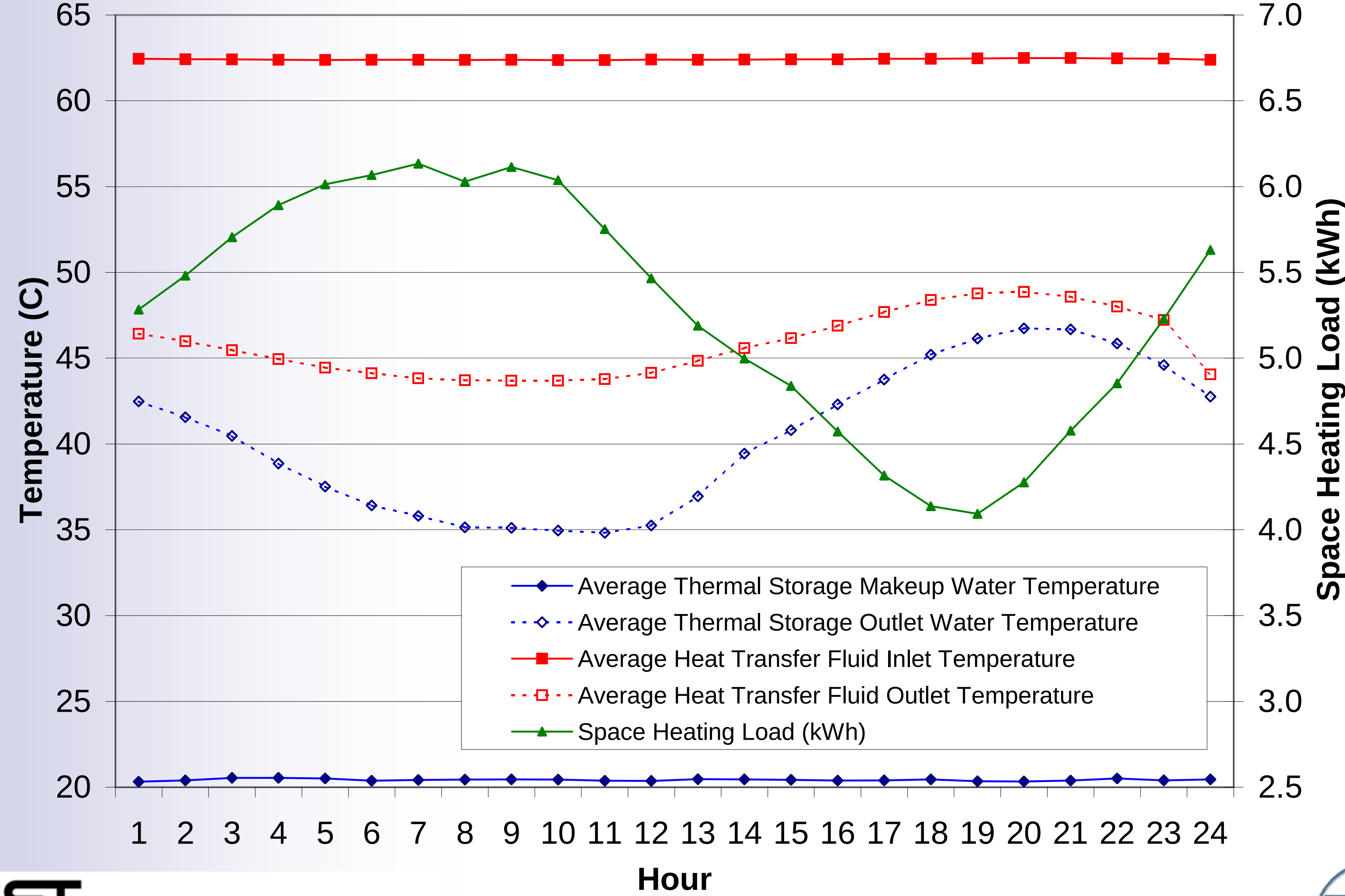
Space Heating Load Performance – 100% Electrical Load in Atlanta



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Electrical Transient Tests

- Description
  - Measured electrical performance during step changes power setting (grid-interconnected) or power output (grid-independent) for all 6 possible permutations
  - Data recorded at 5-second intervals
  - No thermal load extracted to maintain steady conditons
- Results
  - Longest duration between power output levels was 18 minutes, but most were less than 10 minutes
  - Small changes in efficiency during transition measured

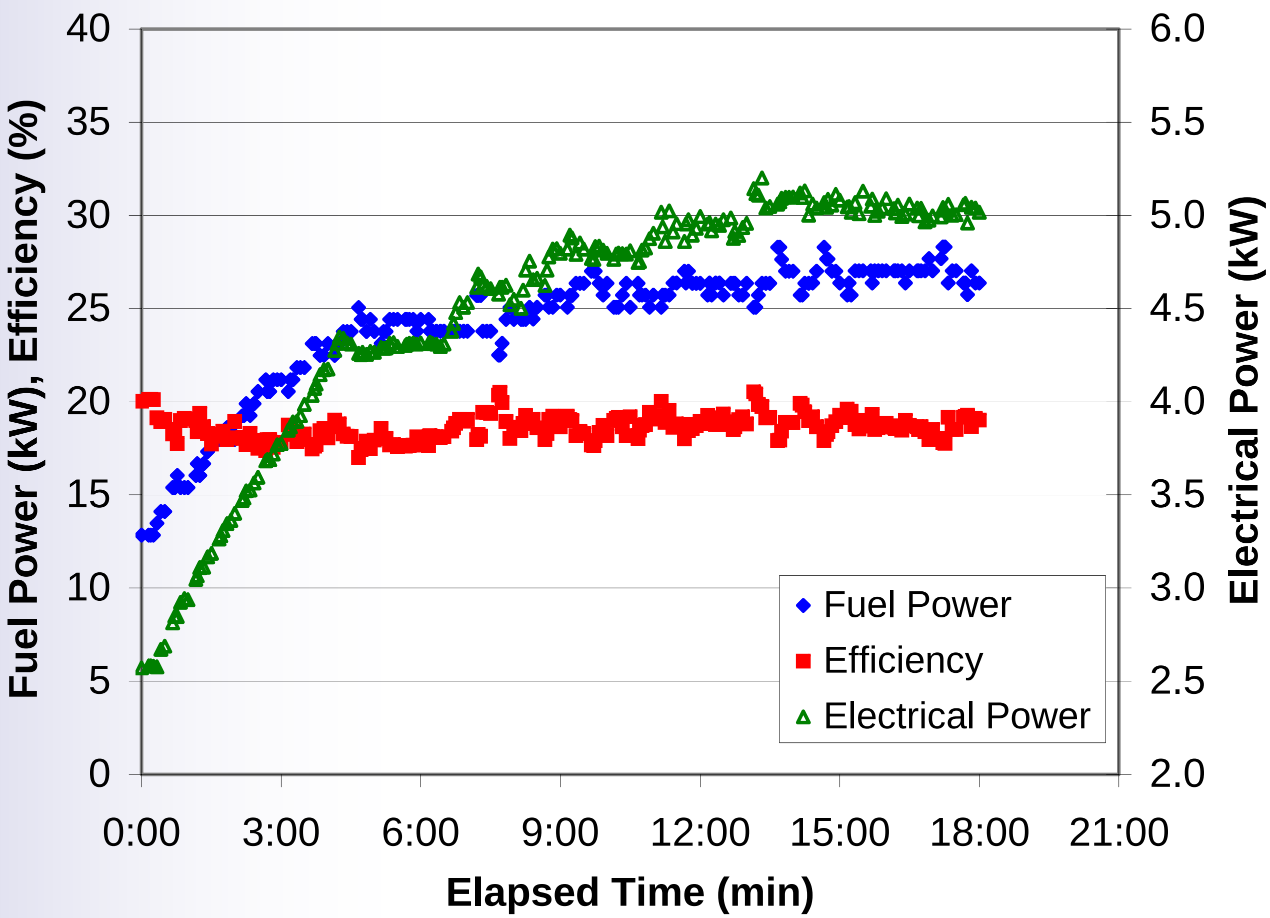
Performance Testing of Residential Fuel Cells

Electrical Transient Tests – Efficiencies before, during and after transition

Steady Electrical Load Fraction	Transition	Grid-Interconnected Electrical Efficiency (%)		Grid-Interconnected Duration (min)	Grid-Independent Electrical Efficiency (%)		Grid-Independent Duration (min)
50		19.4			19.2		
	50 -> 100		18.4	18		20.1	18
100		18.7			18.9		
	100 -> 80		19.5	9		18.8	6
80		19.6			19.8		
	80 -> 50		19.8	8		17.9	6
50		19.8			19.3		
	50 -> 80		19.2	7		20.7	9
80		19.8			19.7		
	80 -> 100		18.7	9		18.9	10
100		19.2			18.8		
	100 -> 50		20.1	18		16.2	7
50		20.2			19.2		

Performance Testing of Residential Fuel Cells

Electrical Transient Tests – 50% to 100% Grid-Interconnected



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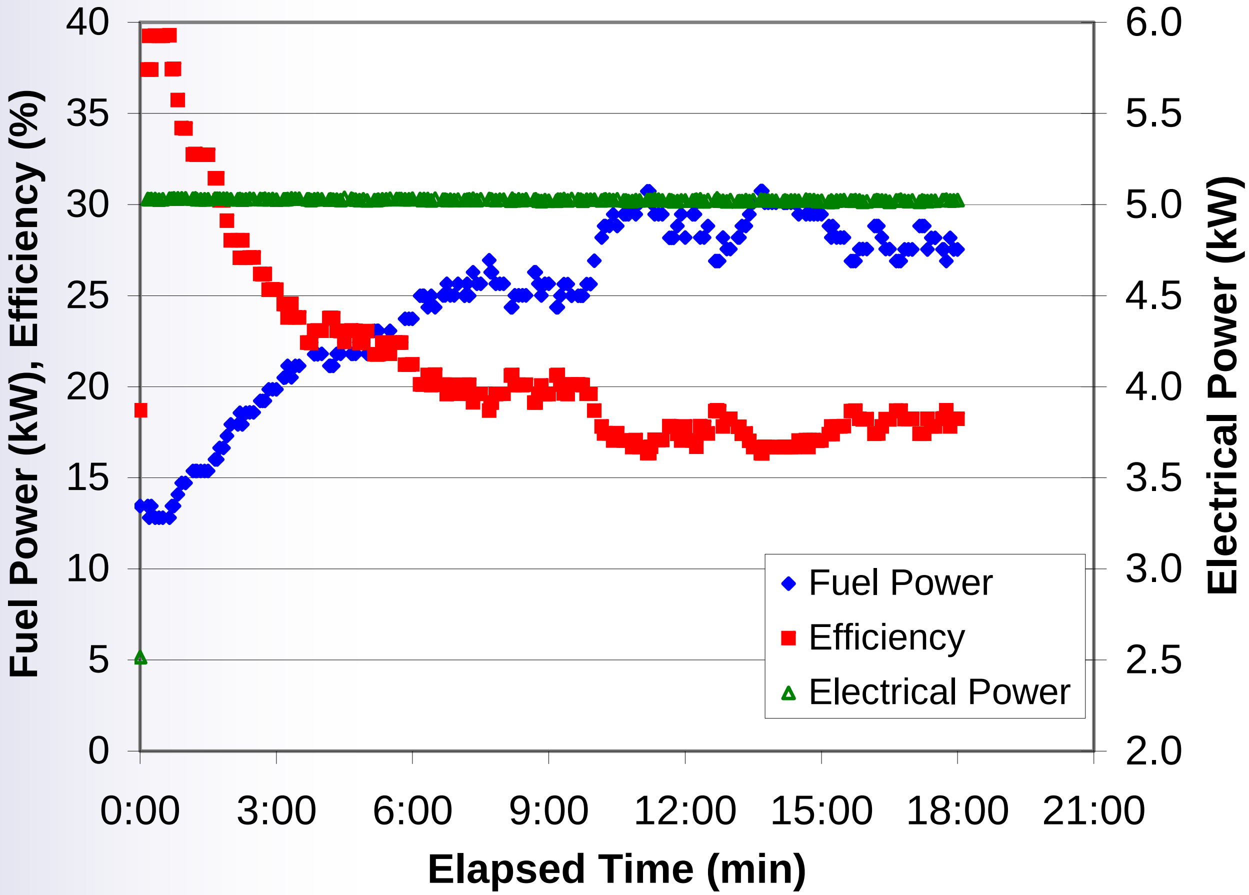
Electrical Transient Tests – 50% to 100% Grid-Independent



Conclusions

- Parameters affecting electrical performance
  - Electrical power output (i.e. load fraction)
  - Degradation over time
- Parameters affecting thermal performance
  - Electrical power output
  - Fluid temperature
  - Fluid flow rate
  - Ambient temperature
- Electrical transients occur relatively quickly and with minimum affect on efficiency

Performance Testing of Residential Fuel Cells

IdaTech EtaGen 5

- **Currently installed in test facility**
- Thermal load-following
  - Electrical and thermal output decreases as fluid temperature rises
- 4.6 kW electrical power
- >8 kW thermal power
- Fueled by natural gas
- Grid-interconnected only